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On the dependence of the iron K-line profiles with luminosity in Active Galactic Nuclei

K. Nandra[1,2], I.M. George [1,3], R.F. Mushotzky[1], T.J. Turner [1,3], T. Yaqoob[1,3]

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[1]Laboratory for High Energy Astrophysics, Code 660, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

[2]NAS/NRC Research Associate

[3]Universities Space Research Association

ABSTRACT

We present evidence for changes in the strength and profile of the iron Kα line in Active Galactic Nuclei (AGN), based on X-ray observations with *ASCA*. There is a clear decrease in the strength of the line with increasing luminosity. This relation is is not due solely to radio power, as it persists when only radio-quiet AGN are considered and therefore cannot be fully explained by relativistic beaming. In addition to the change in strength, the line profile also appears to be different in higher luminosity sources. We discuss these results in terms of a model where the accretion disk becomes ionized as a function of the accretion rate.

Subject headings: galaxies:active – galaxies:nuclei – X-rays:galaxies – quasars:general

1. Introduction

Seyfert 1 galaxies exhibit iron Kα emission lines in their X-ray spectra which are characteristic of relativistic effects in an accretion disk surrounding a central black hole (Tanaka et al. 1995; Yaqoob et al. 1995; Nandra et al. 1997 hereafter N97). These lines can be used as a diagnostic of the innermost regions of AGN, and therefore merit further study in classes other than Seyfert 1s. The iron Kα emission was first studied in detail using the *Ginga* spectra of Seyfert galaxies (Nandra & Pounds 1994 and references therein) and based on these results, Iwasawa & Taniguchi (1993, hereafter IT93) suggested that there may be an X-ray "Baldwin Effect" whereby the equivalent width (EW) of the emission line reduced with increasing luminosity. However, this result has been disputed (Nandra & Pounds 1994) and it was unclear whether the correlation held when emission lines from "quasars" were considered (Williams et al. 1992; IT93). With far greater sensitivity and spectral resolution than *Ginga*, *ASCA* (Tanaka, Inoue & Holt 1994) can be used to provide a more stringent test of such an hypothesis. *ASCA* results for individual sources have been suggestive that this trend might hold (e.g., Elvis et al. 1994; Nandra et al. 1995). However, a systematic comparison requires consideration of a larger number of sources. The results of an analysis of the dependence of iron line properties with luminosity, based on a sample of 39 AGN with broad optical lines, will be the subject of this *Letter*.

2. Results

Our intention is to investigate the iron Kα properties, primarily as a function of luminosity, although other relevant parameters are also considered. N97 have investigated the iron line properties of 18 Seyfert 1 galaxies in detail, and we have used those data here. To extend the range of luminosities, we also include iron line data from a sample of 21 quasars presented by Nandra et al. (1998; hereafter N98). "Seyfert 1 galaxies" are

defined by N97 as AGN with predominantly broad optical lines at redshift $z < 0.05$ and "QSOs" defined by N98 as broad-line AGN at $z > 0.05$. Neither sample is well-selected in the conventional sense, and we will discuss this below. Further details of the analysis of the observations can be found in N97 and N98. In both classes of source, the continuum is well approximated by a power-law in the 3-10 keV band and we use such a parameterization here. In that band, we expect little contamination from other components, with the only major concern being the presence of an iron K-absorption edge from the "Compton reflection" continuum which accompanies the iron line (e.g., George & Fabian 1991). However, that edge is very weak when contrasted against the direct continuum and has little effect on the inferred properties of the iron line (N97). As the signal-to-noise ratio for many of the individual objects, and particularly the quasars, can be rather low, we have assembled mean line profiles for the whole sample and various subsamples for comparison. Following N97, we constructed these by fitting a power-law to the *ASCA* SIS spectra in the 3-10 keV band, excluding the "iron band" from 5-7 keV (all energies are quoted in the rest frame). Such an interpolation allows us to investigate the iron line properties without excessive model dependence. The data/model ratios for each source were transformed into the rest frame in each case, which then permits us to co-add the residuals to produce the mean line profiles.

2.1. Profiles as a function of AGN class

For initial comparison, we show in Fig 1 the mean ratios for the Seyfert 1 galaxies and the QSOs. This splits the sample into low ($z < 0.05$) and high ($z > 0.05$) redshift objects. There is a very clear difference between the two, with the QSOs showing much weaker emission, little evidence for the strong "red wing" characteristic of the gravitational effects of the black hole, and relatively stronger "blue" flux (i.e. emission above the rest energy of neutral iron at 6.4 keV). It has been proposed that the weakness of the emission lines

in some high-redshift AGN may be due to the fact that the X-ray emission is produced in a relativistic jet which is beamed away from the accretion disk. However, it is highly unlikely that this is the sole reason for the difference in the character of the lines in the Seyfert and QSO samples. To demonstrate this we show in Fig 1c and d the line profiles for "radio quiet" and "radio loud" subsamples. "Radio loud" sources are defined by N98 as those having $\log(f_{\rm 5Ghz}/f_{\rm V}) > 1$, where $f_{\rm 5Ghz}$ is the ratio of the flux at 5 GHz and $f_{\rm V}$ the optical flux in the V-band. Radio-loud quasars are often separated from radio-quiet objects, as they contain relativistic jets. It can be seen from these panels that the radio-loud subsample does indeed show weaker line emission. But even when only radio-quiet AGN are considered there is a clear difference between the profiles of AGN at $z < 0.05$ and those which are more distant (note that the N97 sample contains only one radio loud source, and is thus dominated by radio-quiet objects). Another parameter, the X-ray luminosity, is highly correlated with both redshift and radio-loudness in the QSO (and also the combined) sample. We now investigate the dependence of the iron line properties with source luminosity.

2.2. Dependence on luminosity

Fig. 2 shows the line profiles split into 5 bins based on the mean X-ray luminosity of the source in the 2-10 keV band, $L_{\rm X} < 10^{43}$ erg s^{-1} (6 observations of 4 sources, no radio loud source), $10^{43} < L_{\rm X} < 10^{44}$ erg s^{-1} (15 observations of 11 sources, none radio-loud), $10^{44} < L_{\rm X} < 10^{45}$ erg s^{-1} (9 observations of 9 sources, 3 radio loud), $10^{45} < L_{\rm X} < 10^{46}$ erg s^{-1} (4 observations of 4 sources, 1 radio loud), $L_{\rm X} > 10^{46}$ erg s^{-1} (11 observations of 11 sources, 9 radio loud). Clearly then, the vast majority of the radio-loud AGN are present in this highest-luminosity bin. Also shown is the mean profile of the combined Seyfert/QSO sample. This latter plot is dominated by the high signal-to-noise observations of the Seyfert

galaxies, which can be seen by comparing that profile to those of the two lowest luminosity bins, which consist entirely of Seyferts. These three profiles are remarkably similar.

However, there is a clear change in the profile for luminosities $L_{\rm X} > 10^{44}$ erg s^{-1}. The bin with $10^{44} < L_{\rm X} < 10^{45}$ erg s^{-1} shows a weakening of the line emission, particularly at the core and relatively stronger blue flux, but still with evidence for the redshifted wing. At $10^{45} < L_{\rm X} < 10^{46}$ erg s^{-1} we see no longer see any evidence for any red wing, and the peak line flux occurs at an energy higher than 6.4 keV. A gaussian fit to the profile in this bin shows a best-fit energy of 6.57 keV, and is inconsistent with 6.4 keV at $>$ 99 per cent confidence ($\Delta\chi^2$=12.5). The line has weakened further, although we caution that there are few objects in this luminosity bin. Above $L_{\rm X} = 10^{46}$ erg s^{-1}, there is no evidence for *any* line emission and the level of any undetected emission is clearly well below any of the other profiles. Our data therefore strongly imply that the strength of the iron Kα lines in AGN reduces as a function of increasing luminosity confirming the X-ray "Baldwin" effect of IT93. Furthermore, we see good evidence for changes in the profile of the line with luminosity, with high-luminosity sources showing a weaker core and red wing, and stronger blue flux up to the point where the line emission disappears altogether. We quantify the dependence of line EW on luminosity in Fig. 3, which shows the mean EW of the emission lines as a function of X-ray luminosity for the bins described above. Two measures are presented: an estimate of the "core" EW, which has been modeled as a narrow gaussian, and the "total" EW, which is modeled as a relativistic disk-line in the case of the Seyferts, and a broad gaussian in the case of the quasars (N97, N98). There is a strong anti-correlation between the luminosity and EW in both cases. The total EW in particular shows a strong reduction above $L_{\rm x} = 10^{45}$ erg s^{-1}. In the two highest-luminosity bins the core and total EWs are consistent, indicating that the broad wings of the emission line have disappeared (Fig. 2).

2.3. Selection Effects

Our samples may suffer from substantial selection effects and biases due to correlated parameters, as intimated above. The objects are selected from the *ASCA* public archive, and presence in that archive requires no clearly defined scientific criteria. However, the tendency is for the sources to be X-ray selected. Bright sources tend to be observed early in any X-ray mission and thus enter the archives first. Our sample also suffers from a bizarre redshift bias due to selection by the time allocation committees, whereby we are dominated by very low redshift objects ($z < 0.1$) which are X-ray bright and very high redshift sources ($z > 1$) which provide potentially exciting results. The very highest luminosity bin is dominated by radio-loud sources some of which are at very high redshift (z=3-4). Therefore, our changes in profile with luminosity could be attributable to changes with radio-loudness, or redshift. As discussed above, the former cannot fully explain the observed changes, as we do find strong line emission in low-luminosity, radio-loud AGN. Similarly, cosmological epoch seems unlikely to be the sole factor in determining the changes in profile. Below 10^{45} erg s^{-1}, where clear changes in strength and profile are already occuring, the highest-redshift source has $z = 0.129$. Thus redshift-evolution would have to occur extremely rapidly to explain our results. On the other hand a luminosity effect could be the *sole* source of our observed correlation, there being no evidence to the contrary. Above a luminosity of 10^{45} erg s^{-1}, only 2/13 sources show evidence for line emission at all, E1821+643 and MR 2251-178. In the latter case the evidence is rather marginal (N98). In the former there still remains some confusion as to whether some fraction of the line arises from the surrounding cluster, but the emission is probably dominated by the QSO (Kii et al. 1991; Yamashita et al. 1997). On the other hand, all but one (PG 1404+226) of the 24 sources with luminosity below 10^{45} erg s^{-1} show evidence for line emission. The lack of a detection in the case of PG 1404+226 can be attributed to the low signal-to-noise ratio of the spectrum in the hard X-ray band. Another point to consider is that radio-loud QSOs,

which therefore have high-luminosity and high-redshift in our sample, appear to have flatter continuum slopes in the soft X-ray band (Wilkes & Elvis 1987). It is unclear whether or not this effect occurs in the hard X-rays (William et al. 1992; Lawson et al. 1992; Lawson & Turner 1997). Different continua can affect the strength of the iron line in that for flatter slopes, higher EWs are produced (e.g., George & Fabian 1991). We would thus expect *stronger* emission lines in the radio-loud sources if they had flatter hard X-ray slopes, rather than weaker ones, as we observe. We therefore believe that differences in continuum shape cannot account for our results.

3. Discussion

Using a (poorly-selected) sample of X-ray observations of broad-line AGN, we have shown clear evidence of an X-ray "Baldwin" effect, i.e. a reduction in the strength of the iron Kα line with increasing luminosity. Such an effect was originally suggested based on *Ginga* data by IT93. Although the effect could be partially due to beaming of the X-rays away from the putative accretion disk in radio-loud sources, there is still strong evidence for differences between high and low luminosity sources when only radio-quiet objects are considered. We therefore conclude that the primary effect is most likely with source luminosity and discuss the impact of our results in that context. The emission line in low-luminosity AGN is thought to arise from an accretion disk, where Doppler and gravitational effects produce the extreme broadening, and especially the red wing. An alternative origin for a line core at 6.4 keV is in the putative molecular torus which may obscure the line-of-sight to Seyfert 2 galaxies (Ghisselini, Haardt & Matt 1994; Krolik, Madau & Zycki 1994). In principle then, differences in the line profiles could arise from differing contributions from the accretion disk and torus. We observe an effect consistent with this, in that the 6.4 keV peak reduces with increasing luminosity and

largely disappearing above $L_{\rm X} > 10^{45}$ erg s^{-1} (Fig. 3). The upper limit to the EW of any narrow, 6.4 keV line in the highest luminosity bin is ~ 25 eV, so our data are consistent with a small contribution from the torus in all sources, and if that contribution decreased when the luminosity increased it would account for some of the differences in line profiles. However, we also observe an effect that the red wing reduces with luminosity, implying that the disk-line component also changes. Indeed, the entire effect can be attributed to changes in the disk-line.

Nandra et al. (1995) suggested that the lack of significant iron line emission in high luminosity AGN might be due to the fact that those sources have a high accretion rate, causing the disk to become ionized (Matt, Fabian & Ross 1993), with iron being fully stripped. Some support from that hypothesis came with the detection of an emission line consistent with highly-ionized iron in an "intermediate" luminosity QSO, PG 1116+215 (Nandra et al. 1996). Our results are interpretable in this context. For a given black hole mass, higher luminosity sources should have a higher accretion rate, as well as more intense X-ray (ionizing) luminosity. Both would tend to strip atoms in the disk. At some point, iron will begin to be ionized, which should cause more "blue" flux to be observed from high-ionization species. In these intermediate ionization states, resonance scattering can also cause a reduction in the line flux (Matt, Fabian & Ross 1993, 1996). An increase in the effective fluorescence yield in the He-like and H-like states would cause stronger line emission when those species are dominant, but if the emission comes from a range of radii (and therefore ionization state) in the disk, which appears to be the case (N97), that effect may not be clearly observable. At another transition point, iron atoms in the inner disk will begin to become fully stripped, which would cause a reduction in the "red wing" and a shift of the mean energy above 6.4 keV. When iron becomes fully stripped throughout the X-ray illuminated part of the disk, no emission line will be observed from the disk at all. All of these effects are observed in Fig. 2. If this model is correct, we should observe

associated changes in the Compton reflection component (e.g., Zycki & Czerny 1994). As the ionization rises, the disk becomes more reflective in the soft X-ray band, causing a "soft excess", with the potential for associated line emission from elements lighter than iron (e.g. O, Ne). Again, for very high ionization states, we see the Compton reflection without it suffering absorption in the disk, making the "contrast" with the continuum very low, resulting in an apparently-weak Compton hump. Such effects are only easily testable with instruments with better high-energy efficiency than *ASCA*.

Of course there may be significant differences in the black hole mass when moving from low to high luminosity sources. Estimates of the black hole masses of local AGN have been made based on various arguments such as optical/UV line widths, stellar kinematics and maser observations (e.g., Koratkar & Gaskell 1991; Ford et al. 1994; Miyoshi et al. 1995). Interestingly, these masses tend to lie in the region 10^{7-8} $M_{\odot}$, regardless of the technique employed. Larger masses would be expected for the highest-luminosity objects in our sample, since if their emission is isotropic, their luminosities would exceed the Eddington limit unless $M > 10^9$ $M_{\odot}$. However, it is interesting to note that for a 10^8 $M_{\odot}$ hole, the transition to ~ 10 per cent Eddington accretion occurs at 10^{45} erg s^{-1}. This is approximately where Matt et al. (1993) predict that the disk will start to become significantly ionized. and where we begin to see a change in the line profile. Super-Eddington accretion occurs at 10^{46} erg s^{-1}, above which luminosity the emission line disappears. Thus we speculate that the AGN in our sample cover a relatively small mass range, and that the differences in the source luminosities are due to differences in accretion rate, which then affect the line profiles. The implication of this is that the quasar phenomenon is short-lived.

Further exploration of these models awaits the formation of larger, and preferably complete, well-selected samples within the *ASCA* archive, which we anticipate within the next few years.

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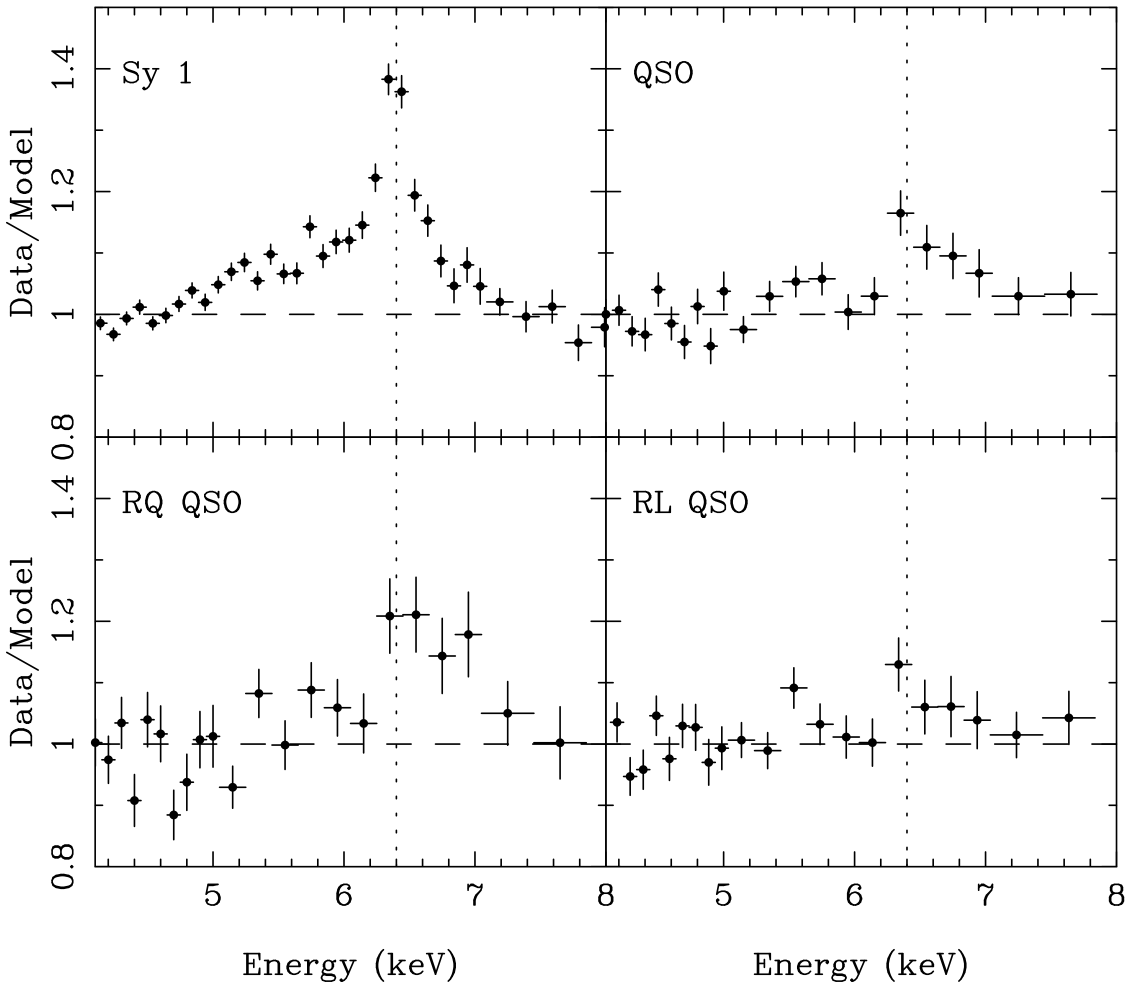

Fig. 1.— Mean data/model ratios, transformed into the rest frame, assuming a power-law fit to the 3-10 keV band in the rest frame, excluding the 5-7 keV "iron band". The upper left panels shows the Seyfert 1 profile (N97). The upper right panel shows the QSOs of N98. The lower left panel shows the "radio quiet" sources from the N98 sample and the lower right the "radio-loud" sources (see text). The vertical dotted lines are at an energy of 6.4 keV. There is a clear difference between the Seyfert 1s and the QSOs, with the latter showing a weaker line, a weaker "red wing" and relatively higher "blue" flux. When radio quiet QSOs are considered alone, differences with the Seyfert 1s remain, with at least the core being significantly different. Radio loud sources exhibit little line emission at all, possibly because this subsample is dominated by very high luminosity objects.

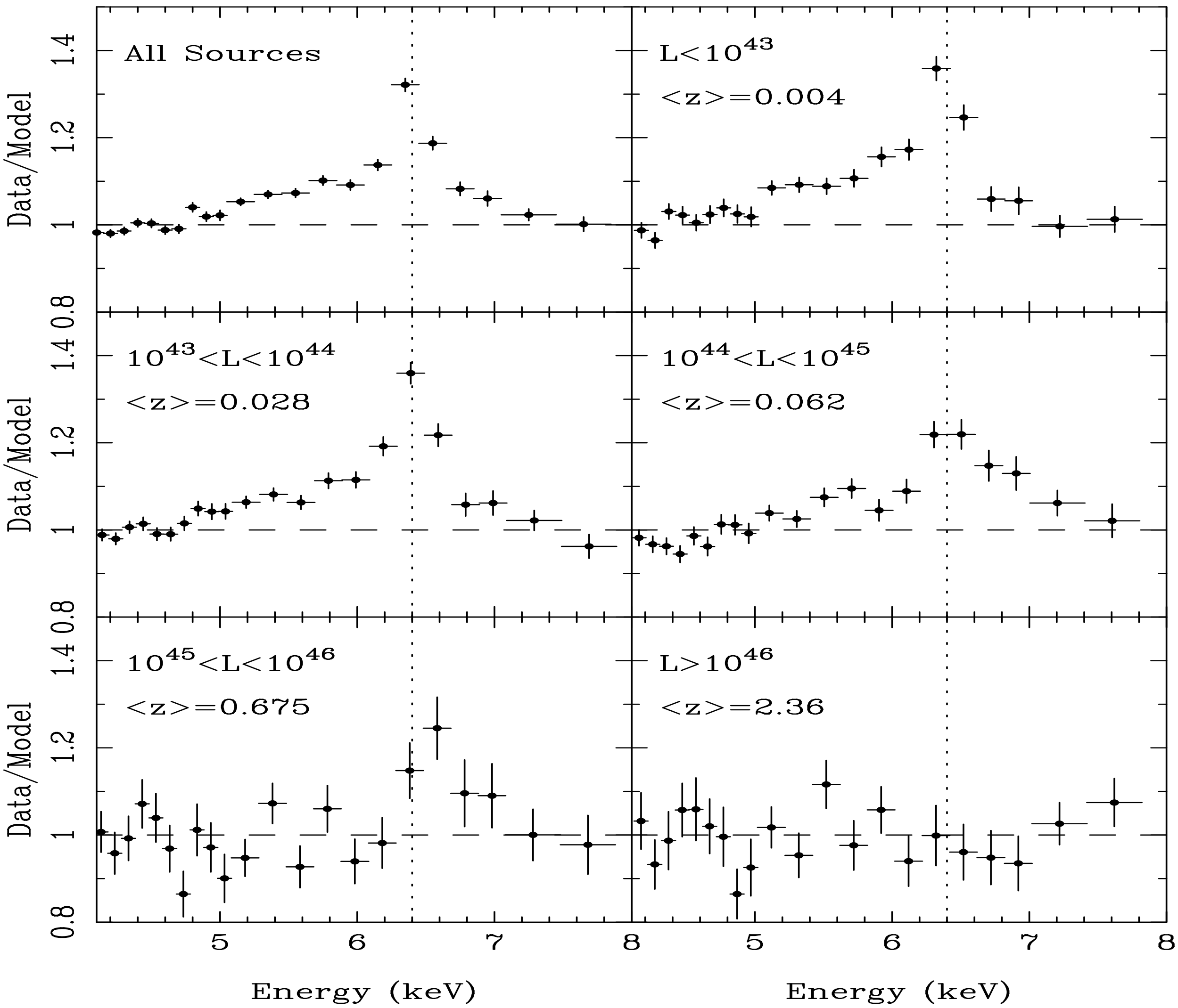

Fig. 2.— Data/Model ratios, constructed as in Fig. 1, split into luminosity bins. The vertical dotted lines are at an energy of 6.4 keV. The profile for all sources (upper left) is dominated by the high signal-to-noise objects which are mostly low luminosity. Below $L_{\rm X} = 10^{44}$ the line profiles are very similar, but above this luminosity there are clear changes. The line strength reduces with increasing luminosity, in both the core and red wing, but the blue flux is enhanced relative to the total line emission. Above $L_{\rm X} = 10^{46}$ no evidence for line emission is observed at all. This confirms the "X-ray Baldwin" effect suggested by IT93. The mean redshift is also shown, and demonstrates the strong correlation between redshift and luminosity in our sample.

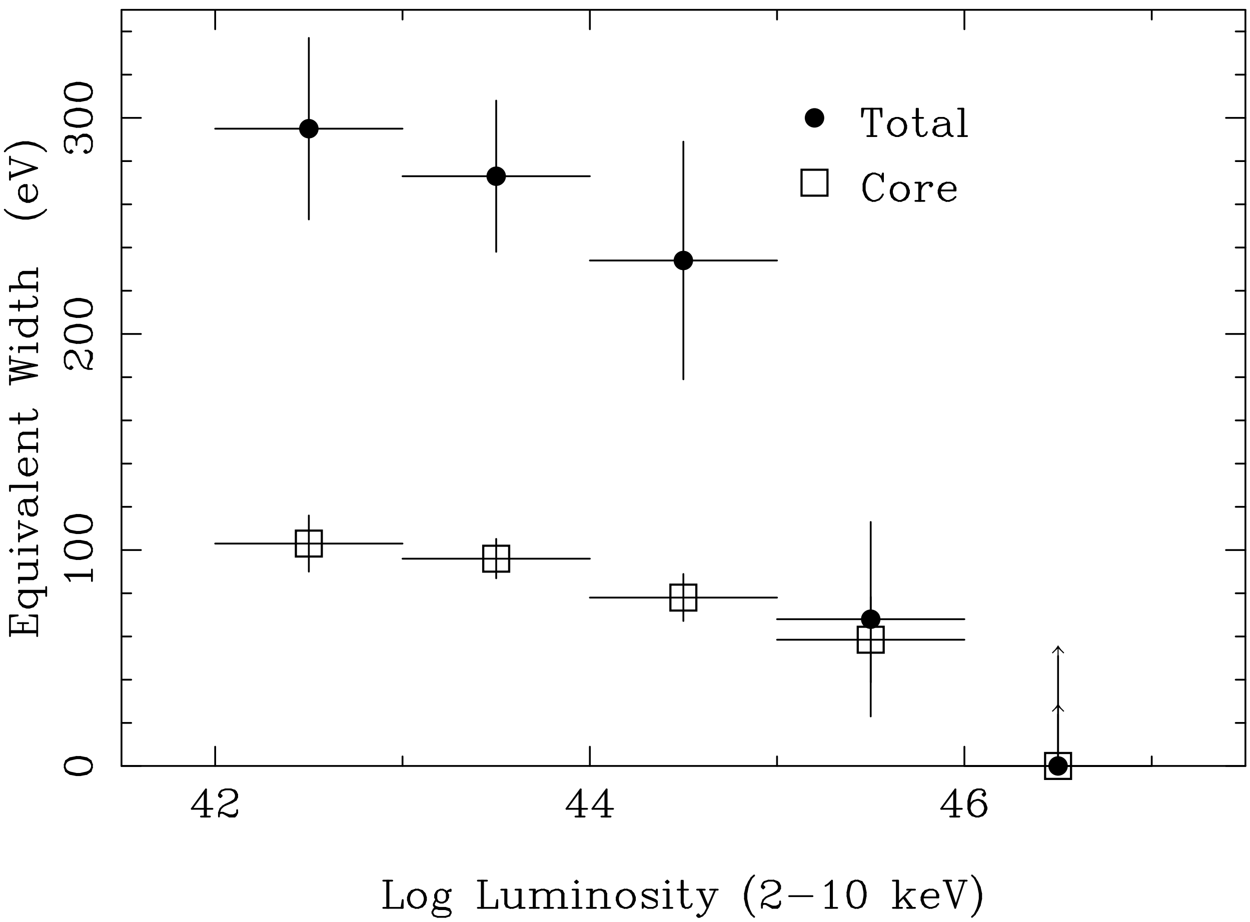

Fig. 3.— Equivalent width of the iron Kα emission lines (rest frame) versus luminosity, binned as for Fig. 2. The open squares show the results for a "narrow" gaussian fit, with upper limits derived for a line at 6.4 keV. These fits tend to model the line core. The solid circles are the equivalent widths for a relativistic disk line in the case of the Seyfert galaxies (N97), and a broad gaussian with free width for the QSOs in which a line is detected (N98). Where no line is detected upper limits were determined for a line at 6.4 keV, with a fixed width of $\sigma = 0.43$ keV, the mean value for Seyferts (N97). These fits will tend to model the total flux of the emission line better than a narrow gaussian, as evidenced by the fact that the EWs are higher. Both the core and total EWs show a clear decrease EW with luminosity. We also note that above $L_{\rm X} = 10^{45}$ erg s^{-1}, the majority of the flux is modeled by a narrow line, consistent with the lack of a "red wing" in the data.